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Transient Analysis of Charging System with Centrifugal Charging Pumps

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ABSTRACT

The CARD (CVCS Analysis for Design) code has been developed for the transient analysis of the letdown and charging system of Korea Standard Nuclear Power Plant. The computer code has been already verified and validated by comparing with actual test results. Analyzed in this paper are the flow and pressure transients in the charging line. The sensitivity studies are performed to select the acceptable control parameters of charging line backpressure controller and seal injection flow controller. In addition, the seal injection system transient is evaluated for the pressurizer auxiliary spray operation. It is shown that the charging line backpressure controller control parameters yield a significant effect on the charging system stability. The results obtained from this study will be used to verify the system design and to select the optimum control parameters for the charging system with centrifugal charging pumps.

1.0 Introduction

The schematic diagram of the charging subsystem of chemical and volume control system (CVCS) for Korea Standard Nuclear Power Plant is shown in Figure 1. The charging pump normally takes suction from the volume control tank (VCT) and discharges into the reactor coolant system (RCS). One charging pump is in operation during normal operation. The charging flow rate is controlled by one of two charging flow control valves located in the charging pump discharge line. The charging flow control valve is automatically controlled by the pressurizer level control system (PLCS) or manually operated. The charging flow is limited by closing the charging restricting orifice bypass isolation valve when the flow is high. A main portion of the charging flow passes through the shell side of the regenerative heat exchanger (RHX) for recovery of heat from the letdown flow. The remainder of the charging flow is diverted for reactor coolant pump (RCP) seal injection. The seal injection fluid is maintained at a relatively constant temperature by flowing through the tube side of a steam heater and then filtered and distributed to the four RCPs.

The CARD code has been developed to simulate the thermal-hydraulic performance of the CVCS under dynamic operating conditions[1]. The RCS boundary conditions for the CARD code are specified with variable temperature and pressure. The CARD code has a modular structure which is composed of generalized standard subroutines for the components such as valves, pumps, orifices and heat exchangers. The code has been verified and validated by comparing the simulated results with the data measured during the letdown system performance test and evaluating charging system behavior[1].

The purpose of this analysis is to evaluate the effects of the control parameters of charging line backpressure controller and seal injection flow controller on charging system transients and to estimate the minimum required charging flow for providing seal water to reactor coolant pumps during auxiliary spray operation. Therefore, in this paper, the analysis focuses on the system transients in the charging line. The sensitivity studies are carried out to determine the acceptable control parameters of charging line backpressure controller and seal injection flow controller. The transients in RCP seal injection system are also evaluated for the auxiliary spray operation.

2.0 Modeling Formulation

2.1 Modeling of Charging System

The charging system is modeled as shown in Figure 1. The modeling of the system is based on nodalization and flowpath networking. The charging system is nodalized into 9 normal nodes, 9 boundary nodes and 20 flowpaths. The regenerative heat exchanger, the seal injection heat exchanger, and the charging pump mini-flow heat exchanger are modeled as the normal nodes and the charging nozzle, the volume control tank, the refueling water tank (RWT), the pressurizer (PZR), the reactor coolant pumps and the equipment drain tank (EDT) are modeled as the boundary nodes. The state parameters such as pressure, temperature and fluid mass are calculated in each node by solving the nodal mass and energy conservation equations, and the flowrates between nodes are calculated by solving the mixture momentum equation in each flowpath. The governing equations are derived based on the assumption of homogeneous equilibrium[2]. The loss coefficient (i.e., flow resistance or K value) at each flowpath is determined to keep the balance of pressures in nodes and flowrates in flowpaths on the normal operation conditions.

2.2 Assumptions in Modeling

The stiction (sticking friction) effect which is expressed as a percentage of the valve full travel length results from the mechanical friction between the valve stem and the packing, and prevents the valve from responding to the demand until the demand signal is larger than the value of stiction. In this analysis the stictions of charging flow control valves, charging line backpressure control valve, and seal injection flow control valves are assumed to be 1.0%, and it is assumed that the letdown system is in normal operation during the transient. It is also assumed that the VCT is an infinite water source. The PLCS is assumed to be in automatic mode, that is, the charging flow control valve is controlled automatically except for the PZR auxiliary spray operation.

3.0 Sensitivity Analyses and Results

3.1 Acceptable Control Parameters of Charging Line Backpressure Controller

The boundary conditions for RCS, PZR, EDT, and VCT are assumed to be normal operational pressures and temperatures. The +5% step change in the pressurizer level is considered as the initiating transient. Therefore, the opening position of charging flow control valve is automatically adjusted by the demand signal of PLCS. The input data are assumed as follows:

- The stroking times of charging line backpressure control valve (CH-240), seal injection flow control valves (CH-241/242/243/244) and charging flow control valves (CH-212P/Q) are 5 sec.
- The control parameters for the seal injection flow controller are 2.5 for proportional gain (PG) and 20 sec for integral time constant (ITC).
- The PLCS is placed in automatic.
- The low and high alarms of charging line backpressure control are 90 psid and 165 psid, respectively.
- The charging line backpressure controller setpoint is 135 psid.

The following 6 cases are evaluated for the proportional gain and integral time constant of the charging line backpressure controller:

a. Case A1 : PG = 0.2 and ITC = 3 sec
b. Case A2 : PG = 0.2 and ITC = 40 sec
c. Case A3 : PG = 1.5 and ITC = 3 sec
d. Case A4 : PG = 1.5 and ITC = 40 sec
e. Case A5 : PG = 3.0 and ITC = 3 sec
f. Case A6 : PG = 3.0 and ITC = 40 sec

The acceptability of the control parameters is determined based on the following criteria :

- The charging line backpressure low and/or high alarms do not occur.
- The charging differential pressure does not oscillate continuously.

The charging flow, seal injection flow and charging line backpressure for Case A2 (PG=0.2, ITC=40 sec) run are shown in Figure 2. As shown in Figure 2(a), the main charging flow is reduced to 45 gpm, and seal injection flow is slightly reduced but recovered soon to 26.4 gpm (6.6 gpm/RCP). Figure 2(b) shows the charging line backpressure control. As shown in Figure 2(b), the charging differential pressure is reduced to 113 psid at initial transient but the low pressure alarm does not occur. The pressure is recovered very slowly to the setpoint (135 psid) as CH-240 opens due to the reduced charging flow. The charging differential pressure transient shows the periodic flips, which result from the stiction of charging line backpressure control valve. The further evaluation shows that the charging differential pressure reaches the setpoint smoothly without stiction of the valve.

The charging line backpressures for Cases A4 (PG=1.5, ITC=40 sec) and A6 (PG=3.0, ITC=40 sec) runs are shown in Figures 3 and 4, respectively. The charging differential pressures are reduced to 116 psid and 123 psid, respectively, at initial transient but recovered to the setpoint instantly. But in Cases A4 and A6, the charging line backpressures oscillate continuously with the range of 8 psi of peak-to-peak pressure because the control parameters are not set properly.

The transient results for Cases A1, A3 and A5 are not addressed in this paper because they have the same trends as Cases A2, A4 and A6, respectively.

According to the above results and the further evaluation, the charging line backpressure yields less severe transient for lower proportional gain of the charging line backpressure controller and it is not sensitive to the integral time constant of the controller. The proportional gain of 1.0 or less and the integral time constant of 3 ~ 40 sec are acceptable for the charging line backpressure controller.

3.2 Acceptable Control Parameters of Seal Injection Flow Controller

The boundary conditions for RCS, PZR, EDT, and VCT are assumed to be normal operational pressures and temperatures. The +5% step change in the pressurizer level is considered as the initiating transient. Therefore, the opening position of charging flow control valve is automatically adjusted by the demand signal of PLCS. The input data are assumed as follows:

- The stroking times of charging line backpressure control valve (CH-240), seal injection flow control valves (CH-241/242/243/244) and charging flow control valves (CH-212P/Q) are 5 sec.
- The control parameters for charging line backpressure controller are 0.2 for proportional gain and 20 sec for integral time constant.
- The PLCS is placed in automatic.
- The low and high alarms of seal injection flow are 6.0 gpm and 7.5 gpm, respectively.
- The charging line backpressure controller setpoint is 135 psid.

The following 6 cases are evaluated for the proportional gain and integral time constant of the seal injection flow controller:

a. Case B1 : PG = 0.2 and ITC = 3 sec
b. Case B2 : PG = 0.2 and ITC = 40 sec
c. Case B3 : PG = 1.5 and ITC = 3 sec
d. Case B4 : PG = 1.5 and ITC = 40 sec
e. Case B5 : PG = 3.0 and ITC = 3 sec
f. Case B6 : PG = 3.0 and ITC = 40 sec

The acceptability of the control parameters is determined based on the following criteria :

- The seal injection flow low and/or high alarms do not occur.

- The seal injection flow does not oscillate continuously.

The charging flows, seal injection flows and/or charging line backpressures for Cases B2 (PG=1.0, ITC=10 sec), B4 (PG=1.5, ITC=40 sec) and B6 (PG=3.0, ITC=40 sec) runs are shown in Figures 5, 6 and 7, respectively. The main charging flows are reduced to 45 gpm and the seal injection flows are maintained to 26.4 gpm (6.6 gpm/RCP). However, as shown in Figure 7, the seal injection flow oscillates with the range of 1.5 gpm of peak-to-peak flowrate for Case B6. The charging line backpressures are not different for three cases even though the control parameters change. The transient results for Cases B1, B3 and B5 are not addressed in this paper because they have the same trends as Cases B2, B4 and B6, respectively.

According to the above results and the further evaluation, the seal injection flow yields less severe transient for lower proportional gain of the seal injection flow controller and it is not sensitive to the integral time constant of the controller. The proportional gain of 1.5 or less and the integral time constant of 3 ~ 40 sec are acceptable for the seal injection flow controller.

3.3 Pressurizer Auxiliary Spray Operation

The charging system transients during the PZR auxiliary spray operation are analyzed to evaluate whether the seal injection flow establishes or not. When the operation of the auxiliary spray is required, the main charging line to RCS should be isolated by closing charging line backpressure control valve (CH-240) and auxiliary spray valve (CH-203) should be opened. The boundary conditions for RCS, PZR, EDT, and VCT are assumed to be normal operational pressures and temperatures. The input data are assumed as follows:

- The stroking times of charging line backpressure control valve (CH-240) and PZR auxiliary spray valve (CH-203) are 5 sec.
- The low and high alarms of seal injection flow are 6.0 gpm and 7.5 gpm, respectively.

The following 2 cases are evaluated:

a. Case C1 : Normal Charging Flow (PLCS automatic)
b. Case C2 : Maximum Charging Flow (PLCS manual)

The charging flow, seal injection flow and auxiliary spray flow for Case C1 run are shown in Figure 8. As shown in Figure 8(a), the main charging flow is reduced to 0 gpm upon closing CH-240 and the seal injection flow is reduced to 2.9 gpm/RCP or less. The auxiliary spray flow is maintained to 82.5-80.4 gpm. Figure 8(b) shows the opening of charging line backpressure control valve, charging flow control valve and seal injection control valves. The valve position of CH-212P is controlled by the PLCS to maintain the pressurizer level and the valve position of CH-240 is closed. The valve position of CH-241/242/243/244 is wide open as the seal injection flow reduces due to low charging backpressure.

The charging flow, seal injection flow and auxiliary spray flow for Case C2 run are shown in Figure 9. As shown in Figure 9(a), the main charging flow is reduced to 0 gpm upon closing CH-240 but seal injection flow is maintained at 6.6 gpm/RCP constantly. The auxiliary spray flow is maintained to 106.1 gpm on closing CH-240 valve. Figure 9(b) shows the opening of charging line backpressure control valve, charging flow control valve and seal injection control valves. The valve position of CH-212P is maintained at initial position and CH-240 is closed. The valve position of CH-241/242/243/244 is maintained at 25% opening.

According to the above results, the normal seal injection flow cannot be made to RCPs if the PZR auxiliary spray valve is opened during normal charging flow. It is also found, based on the further evaluation, that at least the charging pump discharge flow should be maintained greater than 113 gpm in order to provide normal seal injection flow during PZR auxiliary spray operation.

4.0 Conclusions

In this paper, the system transients in the charging line are analyzed. The sensitivity studies are performed to analyze the charging line backpressure controller control setpoints and seal injection flow controller control setpoints. The transients in seal injection system are also evaluated for the auxiliary spray operation.

The analysis results show that the charging line backpressure and the seal injection flow yield less severe transients for lower proportional gains of the controllers and they are not sensitive to the integral time constants of the controllers. The proportional gain of 1.0 or less and the integral time constant of 3 ~ 40 sec are acceptable for the charging line backpressure controller. The proportional gain of 1.5 or less and the integral time constant of 3 ~ 40 sec are acceptable for the seal injection flow controller. It is also found that the charging pump discharge flow should be maintained greater than 113 gpm in order to provide normal seal injection during the PZR auxiliary spray operation.

5.0 References

[1] S. W. Kim and J. S. Ahn, “Development of the CARD Computer Code for the Application to the Design of the CVCS in YGN 5&6”, KOPEC, Feb. 1998.

[2] R. T. Lahey, Jr. and F. J. Moody, “The Thermal Hydraulics of a Boiling Water Nuclear Reactor”, ANS/AEC Monograph Series on Nuclear Science and Technology, ANS, 1977.

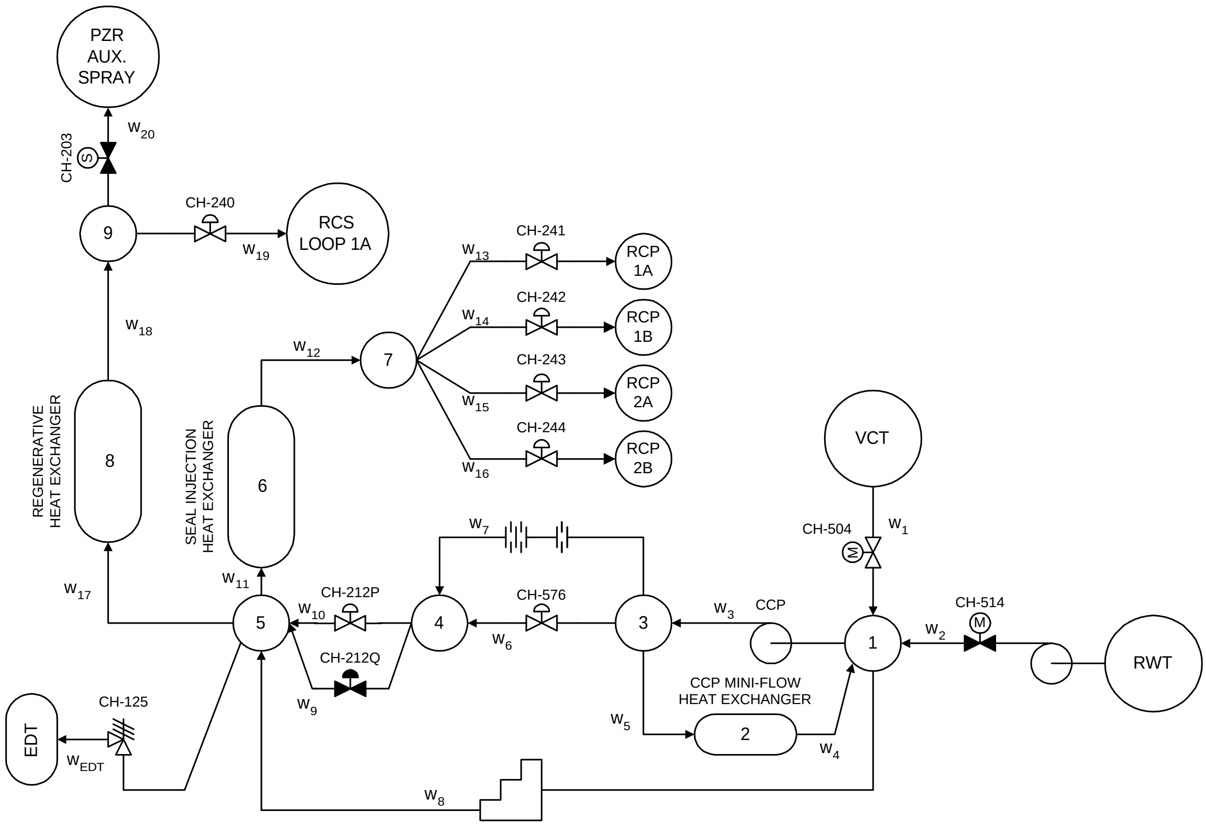
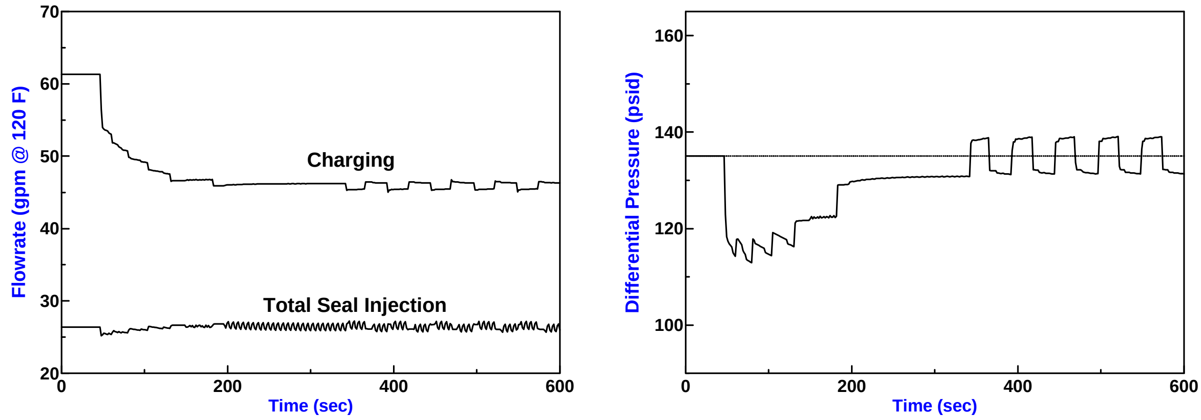


Figure 1. Charging System Nodalization



a. Charging and Seal Injection Flowrates

b. Charging Line Backpressure

Fig. 2. Charging System Transients for PG=0.2 and ITC=40 sec of Charging Line Backpressure Controller

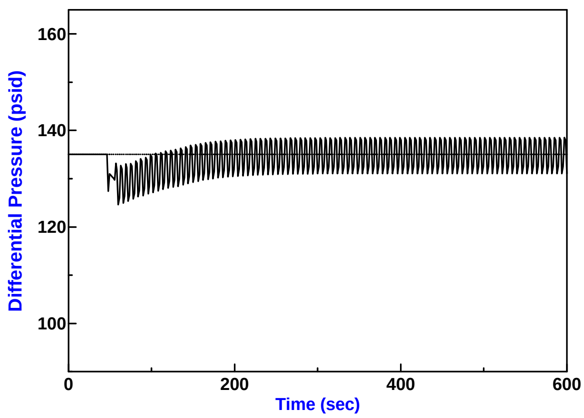


Fig. 3. Charging Line Backpressure for PG=1.5 and ITC=40 sec of Charging Line Backpressure Controller

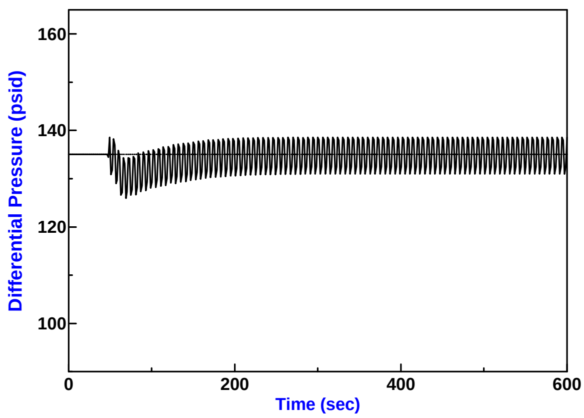
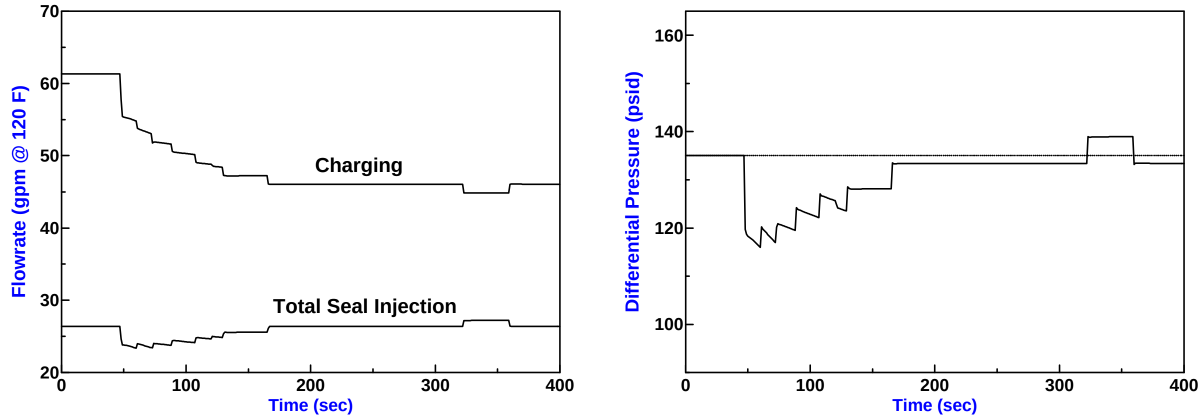


Fig. 4. Charging Line Backpressure for PG=3.0 and ITC=40 sec of Charging Line Backpressure Controller



a. Charging and Seal Injection Flowrates

b. Charging Line Backpressure

Fig. 5. Charging System Transient for PG=0.2 and ITC=40 sec of Seal Injection Flow Controller

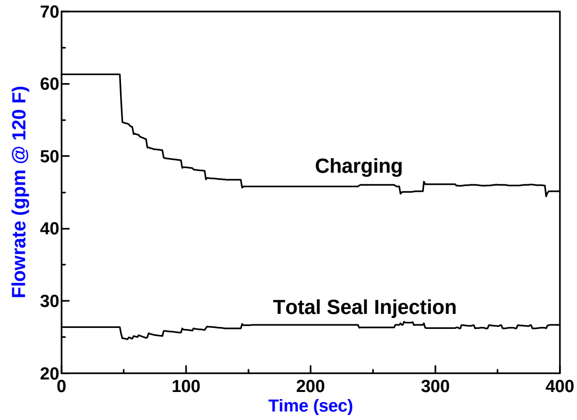


Fig. 6. Charging and Seal Injection Flowrates for PG=1.5 and ITC=40 sec of Seal Injection Flow Controller

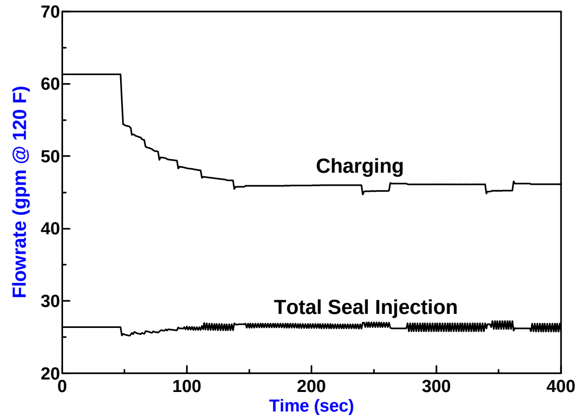
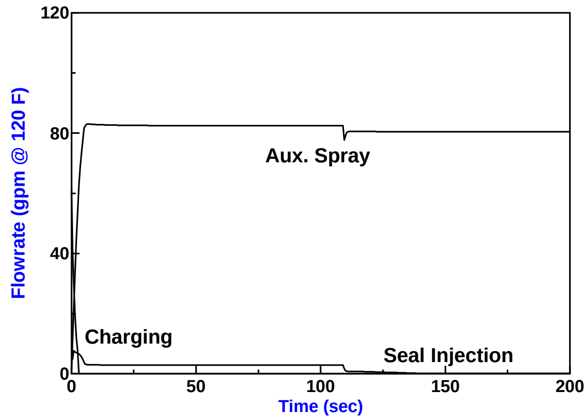
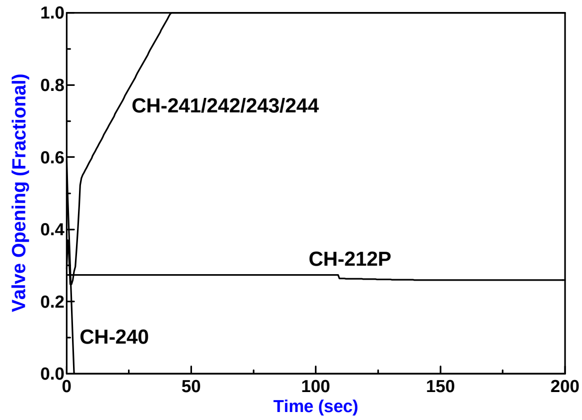


Fig. 7. Charging and Seal Injection Flowrates for PG=3.0 and ITC=40 sec of Seal Injection Flow Controller

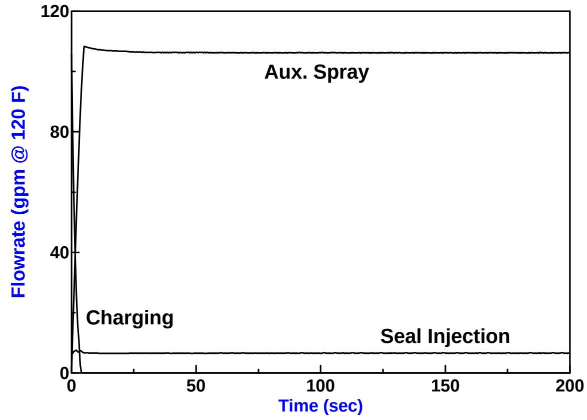


a. Charging, Seal Injection and Aux. Spray Flowrates

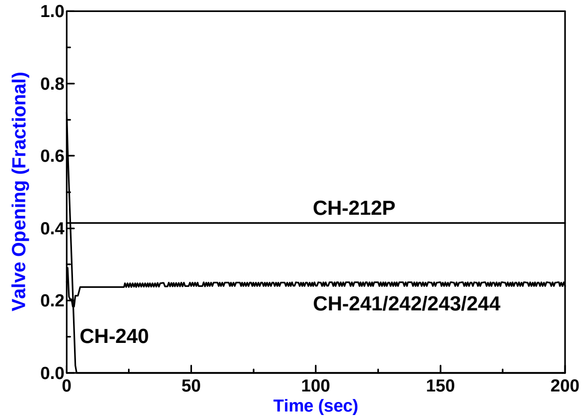


b. Valve Openings

Fig. 8. Charging System Transients during Auxiliary Spray Operation (Normal Charging Flow)



a. Charging, Seal Injection and Aux. Spray Flowrates



b. Valve Openings

Fig. 9. Charging System Transients during Auxiliary Spray Operation (Maximum Charging Flow)